Transfer of Marine-Derived Nutrients by Pink Salmon (*Oncorhynchus gorbuscha*) to Terrestrial Ecosystems in the Shiretoko World Natural Heritage Area, Japan

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Pacific salmon (*Oncorhynchus* spp.) transport marine-derived nutrients (MDN) to terrestrial ecosystems and enhance the biodiversity and productivity of North Pacific ecosystems (Kline et al. 1990; Wipfli et al. 1998). The MDN is incorporated into the terrestrial ecosystems through various pathways. The Shiretoko World Natural Heritage area in eastern Hokkaido is one of few locations where chum (*O. keta*) and pink salmon (*O. gorbusha*) naturally spawn in Japan. Despite the conservation status of the peninsula, salmon upstream escapement has been limited by the construction of a number of artificial structures, such as fish traps and dams. In addition, the contribution of MDN to freshwater and riparian ecosystems is poorly understood in this region. Our objective is to quantify the effect and range of MDN incorporation in the terrestrial ecosystem using stable isotope analysis.

We surveyed two streams on the Shiretoko Peninsula between July-October, 2006-2009. In the Rusha River Pacific salmon, such as pink salmon, chum salmon, and masu salmon (*O. masou*), enter the rivers to spawn in autumn. The escapement of pink salmon to the Rusha River ranged from 10,000 to 58,000 individuals during 2006 and 2008. Although there are three dams on the lower reach, salmon are able to pass each dam. The Akai River, a tributary of the Iwaubetu River system, has dams with a drop of 5 m located 1 km upstream from the mouth. We surveyed the area of the Akai River between these dams, which is inaccessible to spawning salmon. We analyzed carbon and nitrogen stable isotope ($\delta^{13}C$ and $\delta^{15}N$) of organisms in freshwater and riparian habitats of the Rusha River during pink salmon spawning and pre-spawning periods and in the Akai River that has no spawning salmon. To identify pathways of MDN uptake, we examined the stomach contents of Dolly Varden (*Salvelinus malma*) using the index of relative importance (IRI; Pinkas et al. 1971), counted the number of pink salmon carcasses, and classified their mode of transport. The MDN enrichment of organisms in the Rusha region was calculated by a mass-balance equation (Chaloner et al. 2002).

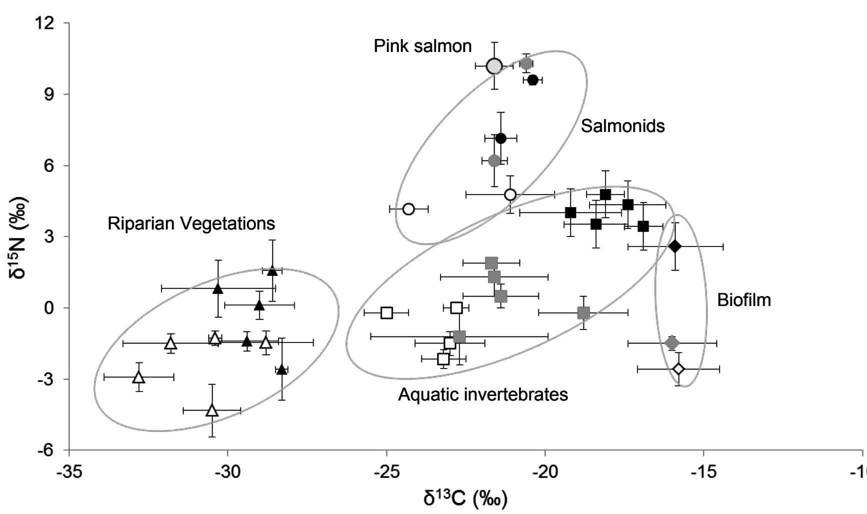

Fig. 1. Trophic shifts of freshwater biota in Rusha River (pink salmon spawning and pre-spawning periods) and Akai River (no spawning salmon). Solid symbols: Rusha River (salmon spawning period); shaded symbols: Rusha River (pre-spawning period); open symbols: Akai River (no spawning salmon).

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In freshwater, stable isotope values for the biofilm and aquatic invertebrates were higher during the spawning period in the Rusha River than during the pre-spawning period in the Rusha River, or in the Akai River (Fig. 1, $p < 0.05$). The $\delta^{15}N$ values for Dolly Varden were more than 9‰ throughout the year in the Rusha River, but only 4.8‰ in the Akai River (Fig. 1). In the Rusha River, Dolly Varden fed mainly on aquatic invertebrates during the pre-spawning period (Fig. 2). However, they shifted from aquatic invertebrates to pink salmon eggs and sea lice during the salmon spawning period.

Results of stable isotope analysis using the growth section analysis method (Mizukami et al. 2005) indicated the feeding history of brown bear was classified as four types: marine, terrestrial, marine to terrestrial, and marine and terrestrial. The nitrogen stable isotopic values of riparian willow (*Salix* spp.) were negatively correlated with the distance from the Rusha River ($R^2 = 0.90$, $p < 0.05$; Fig. 3). The proportion of MDN enrichment that could be traced to pink salmon averaged 25%. We counted a total of 412 bear-killed and 1024 senescent pink salmon carcasses in the riparian area between 22 September and 8 October, 2009 (Fig. 4). Transport of the salmon carcasses to the riparian zone was associated with a heavy rain event on 2nd and 3rd October, 2009, during which precipitation exceeded 100 mm and the water level increased rapidly to 90 cm in the Rusha River (Fig. 5).

In summary, pink salmon import MDN to the freshwater and riparian ecosystems of the Rusha River. In our study, this was evidenced by higher $\delta^{15}N$ values in the aquatic organisms during the spawning period in the Rusha River compared with those in the Akai River, which does not have spawning salmon. Dolly Varden shifted their prey to consumption of salmon eggs during the spawning period. This suggested that pink salmon eggs represent an important food source for Dolly Varden to overwinter. Thus, the spawning migration of salmon may change the food-web structure of freshwater ecosystems. All bears analyzed were categorized into four feeding history types and almost all brown bears fed heavily on pink salmon in the autumn. Riparian vegetation derived 20% of their nitrogen from salmon. We observed a progressive decline in $\delta^{15}N$ values in riparian willows as the distance from the river increased, suggesting that the majority of MDN was assimilated by the vegetation within 50 m of the river. In addition, physical processes also affected material transport into the riparian area. In our study, more than twice the number of carcasses was transported into the riparian zone by flooding than by bears. Thus, flooding events play an important role in transporting salmon carcasses over a long distance and incorporating MDN into the riparian ecosystem. The MDN enrichment of organisms in the Rusha River region was typically lower than those in North America (Kline et al. 1990, Chaloner et al. 2002). This difference may be caused by the artificial constructions in the Rusha River.

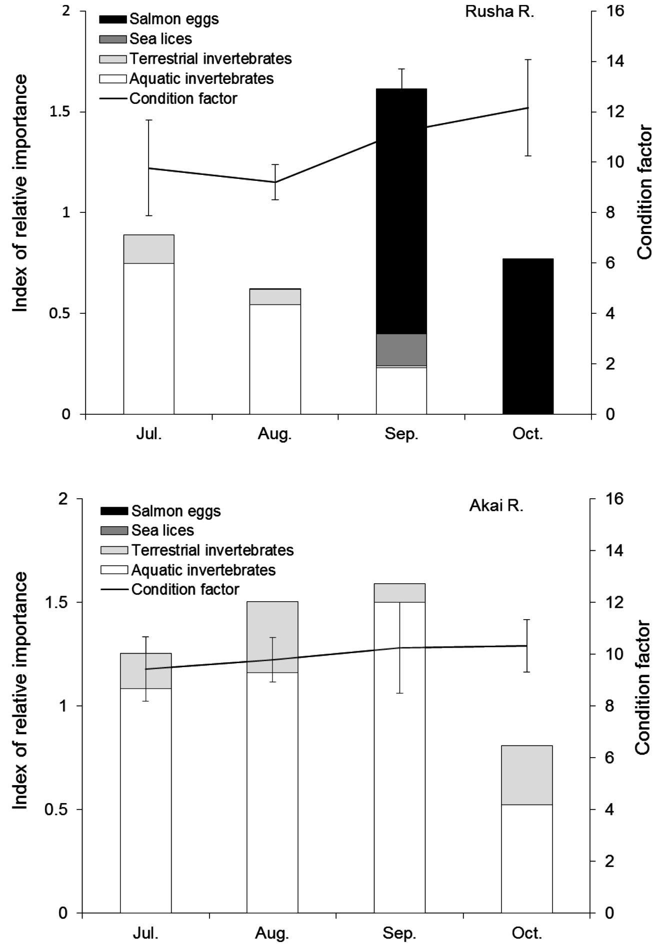

Fig. 2. Monthly changes in the index of relative importance (columns) and condition factor of Dolly Varden (mean ± 1 standard error) in the Rusha (upper panel) and Akai (lower panel) Rivers, July-October, 2007-2008. The IRI is an indicator of the relative importance of prey animals in the diets of a predator (Pinkas et al. 1971).

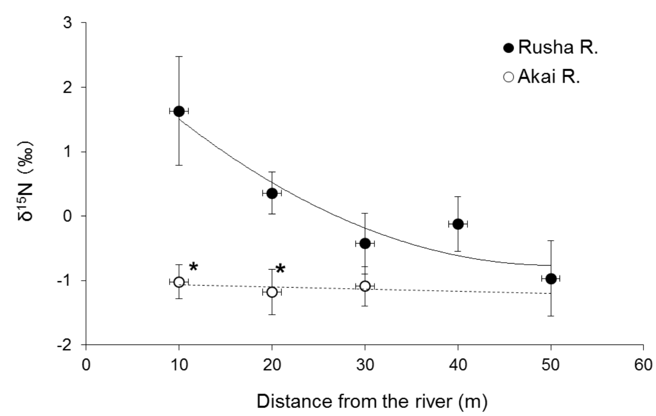

Fig. 3. Relationship between the distance from the river and $\delta^{15}N$ values of willow leaves in the riparian zone of the Rusha River ($y = 0.0014x^2 - 0.1402x + 2.7701$, $r^2 = 0.90$) and Akai River ($y = -0.0035x - 1.0267$, $R^2 = 0.19$). Data: mean ± 1 S.E.* $p < 0.05$.

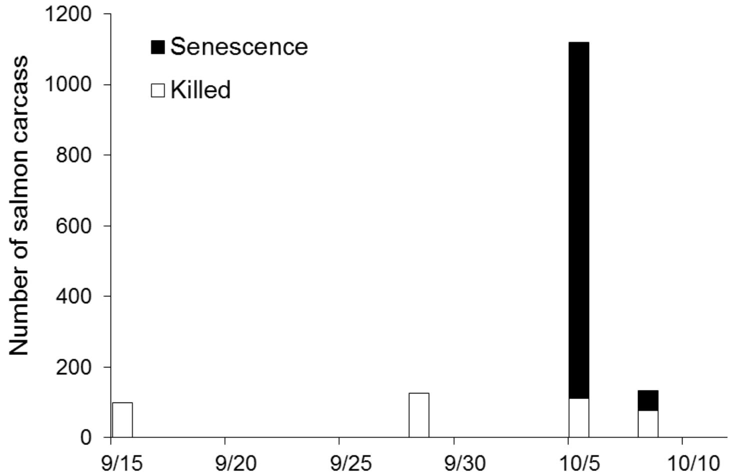

Fig. 4. Number of pink salmon killed by bears or following senescence and deposited in the riparian area of the Rusha River, 2009.

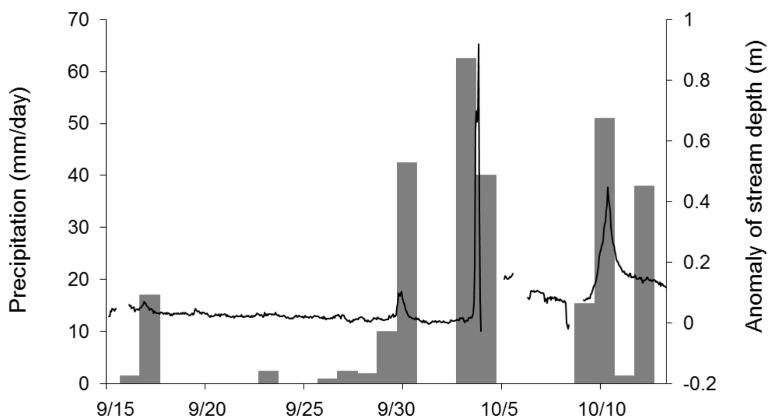

Fig. 5. Temporal change in stream water level (anomaly, shown by the line) of the Rusha River and precipitation (column) during the pink salmon spawning season, 2009.

In conclusion, the MDN transported by pink salmon are incorporated into the majority of trophic levels via several pathways in the terrestrial ecosystem around the Rusha River. To evaluate the significance of escapement of wild salmon to terrestrial ecosystems, it is critical to understand how freshwater and terrestrial pathways interact.

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